



## Conference Paper

# Luders Deformation Mechanisms on Yield Point in X80 Grade Pipeline with Ultrafine Structure

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## Abstract

Strain ageing in X80 grade pipeline with ultrafine ferrite-bainite structure by Digital Image Correlation (DIC) technique at tensile test has been studied. Three types of Luders deformation mechanisms on yield point were observed using DIC fields analysis. It was determined that mechanical behavior of the material on uniform parabolic stage of deformation strongly depends on Luders deformation mechanism type.

**Keywords:** X80 grade pipeline steel, stress-strain curve, discontinuous yielding, Luders deformation, Digital Image Correlation analysis, strain ageing

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## 1. Introduction

Development of high strength steels for the new generation of gas pipelines designed for a high operation pressure is subject of many studies in pipeline and pipe making industries [1-3]. Steady increase of technical requirements to a wide complex of mechanical properties determining reliability of a pipeline has resulted in essential achievements in V, Nb, Ti-microalloyed low and extra-low carbon pipeline steels. Secondary refining and continuous casting followed by thermo-mechanical controlled processing (TMCP) with strict temperature-reduction route and post-deformation cooling rate control are used to produce X80 and a higher grade pipes with ultrafine ferrite-bainite (fully bainite) structure. The X80 grade steels were found to exhibit good combination of strength, high plasticity and toughness [4-5].

However discontinuous yielding has been frequently observed in such materials [6-8]. It occurs during the pipe making process after cold forming followed by anti-corrosion coating at 200-250°C. Mechanism of discontinuous yielding consists in localized Lüders bands propagation along the tensile axis of the specimen. On the

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microstructural level the formation of Lüders bands, their distribution and the related features of the stress-strain curve (the sharp yield point and yield plateau) are associated with an increase in the number of mobile dislocations due to their unlocking or multiplication. Digital Image Correlation technique has been usually used for tensile tests to obtain the plastic deformation component distribution in time on the specimen surface as inelastic strain fields or profiles [9-10].

The aim of this study is to define the features of different Lüders band mechanisms by DIC analysis in X80 grade pipeline steel.

## 2. Research Material and Methods

The material used for the present study was API X80 grade low-carbon steel with 0,08 %wt.C – 1,85%Mn – 0,13%Mo – 0,10%(Ti-V-Nb) chemical composition. After TMCP and subsequent accelerating cooling such steel had ultrafine ( $\sim 3\text{--}5\ \mu\text{m}$ ) ferrite-bainite structure. Flat specimens with 3 mm thickness, 20 mm width and 60 mm calculated length were used for tension tests with strain rate  $\dot{\epsilon} = 2,7 \cdot 10^{-4}\ \text{s}^{-1}$  on Instron 8801 machine equipped with Strain Master System for DIC analysis.

In present work only plastic deformation component  $\epsilon_{yy}$  which correspond to elongation was used to observe plastic flow on stress-strain curve up to tensile strength point. Besides DIC technique involve the analysis of profiles  $\epsilon_{yy}$  values (DIC profiles) along the tension axis.

Specimens has been subjected by various heat treatment routes to achieve the stress-strain curves with contrast discontinuous yielding parameters:

specimen I –  $t = 680^\circ\text{C}$  without holding  $\rightarrow$  air cooling,

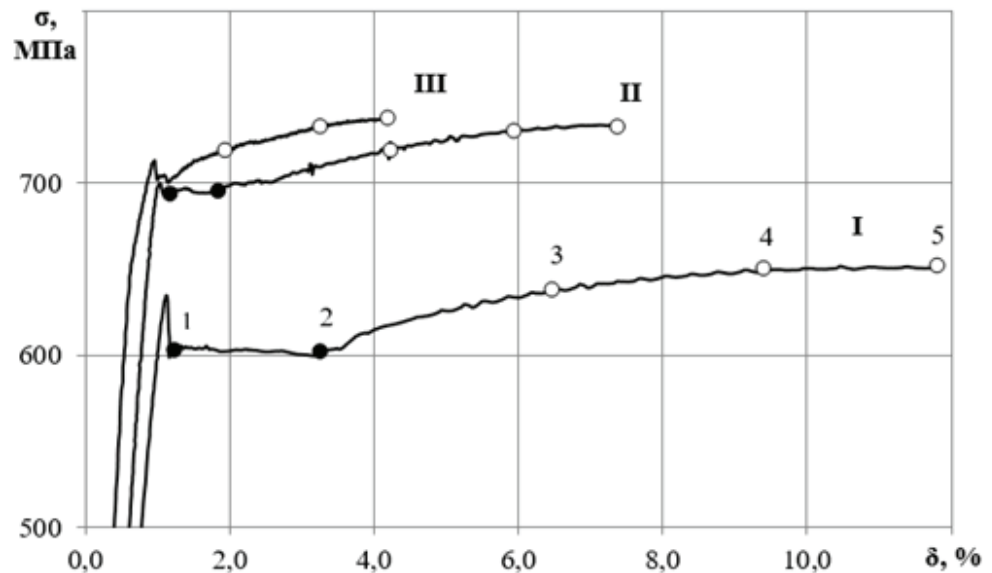
specimen II –  $t = 1000^\circ\text{C}$ ,  $\tau = 0,5\ \text{h}$ .  $\rightarrow$  water cooling  $\rightarrow t = 680^\circ\text{C}$ ,  $\tau = 0,5\ \text{h}$ .  $\rightarrow$  air cooling,

specimen III –  $t = 1000^\circ\text{C}$ ,  $\tau = 30\ \text{min}$ .  $\rightarrow$  air cooling.

## 3. Results and Discussion

Tensile stress-strain curves at room temperature of X80 steel specimens are shown in Fig. 1. It is evident that the specimens have as a different deformation behavior as on a yield point as during uniform stage. Specimen I have a low strength ( $Y_S = 605\ \text{MPa}$ ,  $T_S = 650\ \text{MPa}$ ) but a high plasticity ( $Y_E = 2,0\ \%$ ,  $U_E = 8,1\ \%$ ). Strain ageing enhancement from

specimen I to III leads to increase of strengthening and loss of plasticity at discontinuous yielding (marks 1 and 2 on fig. 1) and uniform plastic stage (marks 3-5 on fig. 1).



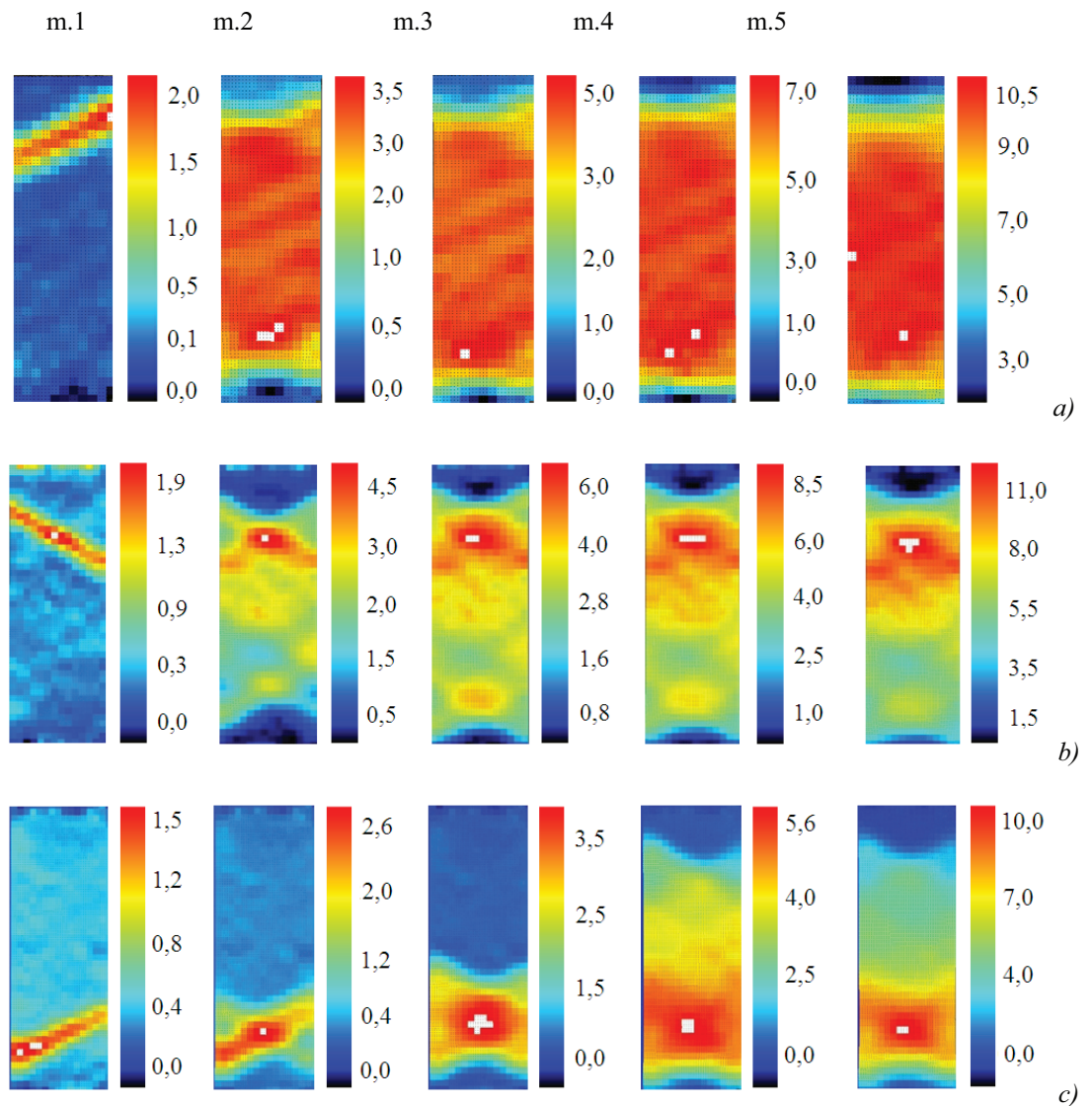
**Figure 1:** Stress-strain curves of X80 steel specimens with different strain ageing value: marks 1–2 – yield point, marks 3–5 – uniform deformation.

As known plastic flow at the yield point is passes by propagation of Luders bands the number of which depends on alloy composition and test conditions. DIC strain fields of  $\epsilon_{yy}$ -component are testified that the Luders deformation is realized by 1 band in specimen I, 6 cross bands in specimen II and 2 cross bands in specimen III (Fig. 2).

Luders deformation in specimen I consist of creation band embryo and its growth through activation of plastic flow channels and continuous deformation in them (marks 1-2 on fig. 1 and fig. 2a). Four plastic flow channels with microstress concentrators were formed on elastic stage yet and periodically located along specimen length. Up to the end of yield point the plastic flow occupied all calculated length. Plastic flow channels with  $\epsilon_{yy} = 3,1-3,8$  % looks like color bands on DIC fields (fig. 2a) correspond with 4 peaks on  $\epsilon_{yy} = f(L)$  profiles (fig. 3a).

Character of plastic component  $\epsilon_{yy}$  distribution did not change on uniform stage of specimen I (marks 4-5 on fig. 2a and fig. 3a) except the essential increase of  $\epsilon_{yy}$  values on  $\epsilon_{yy} = f(L)$  profiles and their alignment along calculated length.

Luders deformation in specimen II realized by creation, movement and crossing of several bands. It was observed the only Luders band at the beginning of yield point (mark 1 on fig. 2b) which correspond with maximum  $\epsilon_{yy}$  value ( $\sim 2,0$  %) at the center of

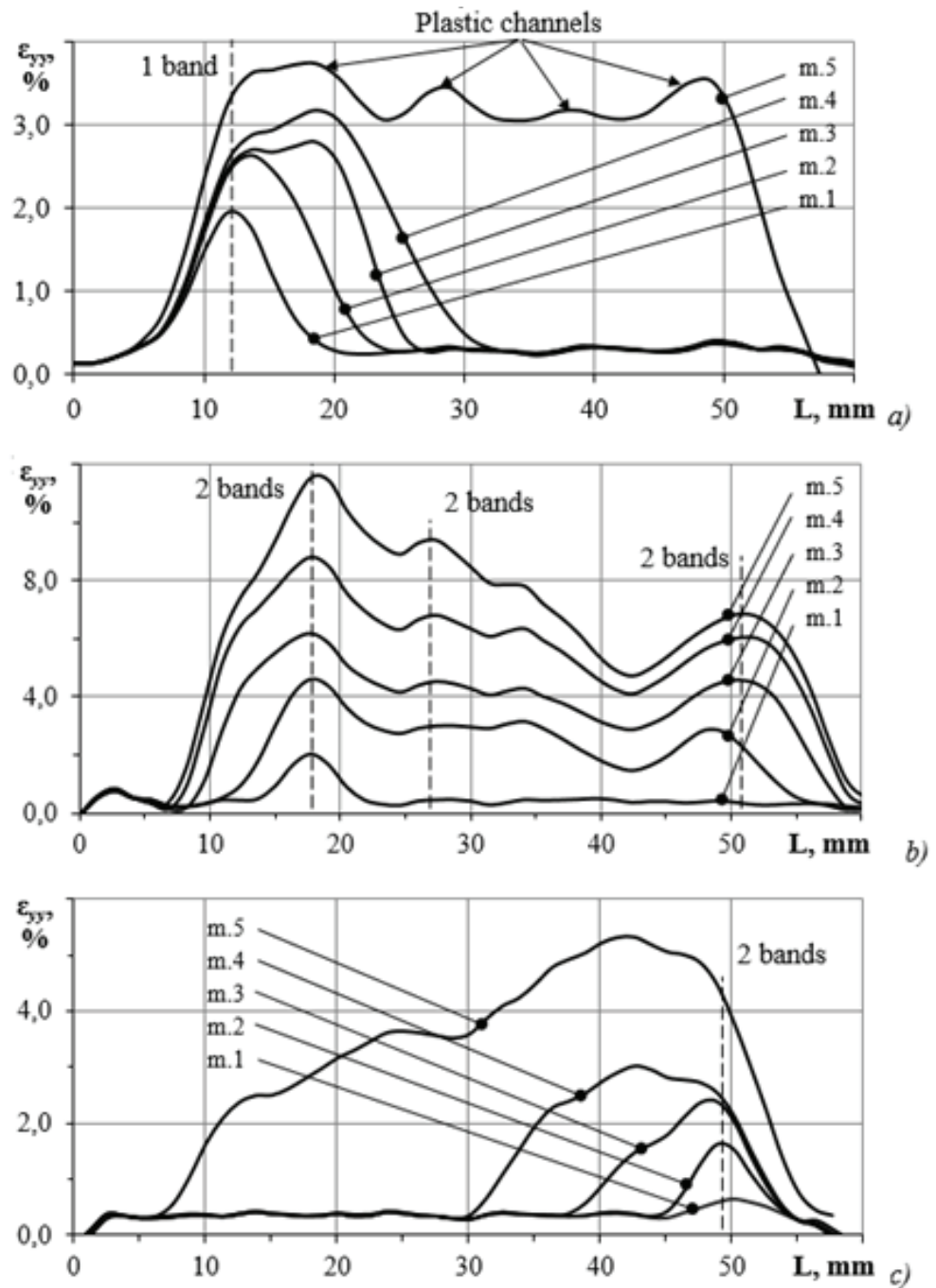


**Figure 2:** DIC fields of plastic deformation component  $\epsilon_{yy}$  at the yield point (marks 1 and 2 on fig. 1) and at uniform stage (marks 3–5 on fig. 1): *a* – specimen I, *b* – specimen II, *c* – specimen III.

calculated length on DIC profiles (fig. 3b). Plastic flow in initial band led to creation of second Luders band and then to their crossing.

This process continues through all yield point resulting in the formation of 6 Luders bands (mark 2 on fig. 2b). Crossing of opposite bands create a strain concentrators which correspond with four peaks on DIC profiles (fig. 3b). On uniform stage strain concentrator which has been created by crossing of the first two bands absorbed the neighboring ones (marks 3-5 on fig. 2b and fig.3b).

Maximum strain ageing effect was observed in specimen III (fig. 1). Luders deformation began with creation of the first band (mark 1 on fig. 2c) and finished when the second band was crossed by the first one (mark 2 on fig. 2c). Plastic flow in resulting standing



**Figure 3:** DIC profiles of component  $\epsilon$  through the center of calculated specimen length  $L$ : *a* – specimen I, *b* – specimen II, *c* – specimen III.

stress concentrator (marks 3-5 on fig. 2c and fig. 3c) determine elongation on uniform stage.

## 4. Conclusion

Differences in the form of stress-strain curves and DIC parameters of X80 grade pipeline steel are due to strain ageing value which in turn depends on density of free dislocations and their locking by atmospheres of C atoms and dispersed carbides. The weakest strain ageing was observed in specimen I where heating on 680°C and subsequent water cooling led to locking of dislocations slip by only MeC type carbides. It is determined such a Luders deformation mechanism when the only one band passed through all calculated specimen length.

Change deformation mechanism in a yield point happens in specimens II and III subjected to heating on 250°C. Simultaneous locking of dislocations slip by atmospheres of C atoms and dispersed carbides  $\text{Fe}_3\text{C}$  led to plastic flow at the yield point not only by creation Luders bands but plastic deformation in the center of their crossing.

Finally Luders deformation mechanism at the yield point determines deformation behavior on the uniform stage of stress-strain curve in particular its extension (uniform elongation value) and necking.

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